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AFRL-ML-TY-TR-1999-4530

REPLACEMENT COATINGS FOR AIRCRAFT ELECTRONIC CONNECTORS: FINDINGS AND POTENTIAL ALTERNATIVES REPORT

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	25 Nov 98	Final Report

4. TITLE AND SUBTITLE Replacement Coatings for Aircraft Electronic Connectors: Findings and Potential Alternatives Report	5. FUNDING NUMBERS F33615-95-D-5615 PE 62102F
6. AUTHOR(S) Naguy, Tom; Slenski, George; Keenan, Robert; Chiles, Gary	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (1) AFRL/MLQE (WPAFB OH 45433) (2) AFRL/MLSA (WPAFB OH 45433) (3) Science Applications International Corp. 11251 Roger Bacon Drive M/S R-4-3 Reston VA 20190	8. PERFORMING ORGANIZATION REPORT NUMBER SAIC # 01-0824-08-5227
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Tom Naguy AFRL/MLQE WAFB OH 45433	10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-ML-TY-TR-1999-4530
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited (PA Case No# 99-022)	12b. DISTRIBUTION CODE A

13. ABSTRACT *(Maximum 200 words)*

The goal of the project this report describes is to identify potential alternative coatings for connectors. This report addresses issues associated with cadmium-plated connectors bonded to aluminum airframes, including:

1. Unacceptable (off-spec) electrical bonds.
2. Flight or system safety impacts.
3. Environmental, health and safety concerns.

The report represents the results of telephone surveys with Original Equipment Manufacturers and major suppliers to determine how they have addressed these issues.

Finally, this report presents a wide range of candidate replacement materials. There are no alternatives identified in this report that greatly exceed cadmium as replacements on electrical connectors. Over half of the coating replacements contain nickel or require a nickel underplate. If nickel alloys are considered, the alloys traditionally used for contacts (palladium-nickel) may be worthy of further investigation. A proprietary formulation of nickel-Teflon® should be examined. IVD aluminum and electrodeposited aluminum appear to be good candidate replacements. Hybrid connectors are an interesting alternative, combining the benefits of aluminum-plated connectors with composite connectors.

14. SUBJECT TERMS Aircraft Electronic Connectors, cadmium-plated connectors, aluminum airframes, palladium-nickel, indium-nickel, nickel-Teflon ®, IVD aluminum, electrodeposited aluminum	15. NUMBER OF PAGES 62 16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

Executive Summary

The goal of the project this report describes is to identify potential alternative coatings for connectors. This report addresses issues associated with cadmium-plated connectors bonded to aluminum airframes, including:

- ❑ Unacceptable (off-spec) electrical bonds.
- ❑ Flight or system safety impacts.
- ❑ Environmental, health and safety concerns.

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1 Introduction

1.1 Project Objective and Goals

Project Objective

The objective of this project is to identify alternative coatings to cadmium for aircraft electronic connectors.

The majority of aluminum connectors on Air Force weapon systems are plated with cadmium. The cadmium coating provides corrosion protection and an electrically conductive surface for the connectors. However, an Air Force laboratory study concluded that bonded cadmium and aluminum surfaces allow the formation of an oxide layer, an insulator, which causes electrical bond deterioration (Ziegenhagen 1997a). Other studies suggest that cadmium and aluminum form a galvanic cell that creates an electrically insulating aluminum oxide (Woodrow 1996). Bond deterioration in an electronic grounding path is *not acceptable* because it can lead poor electromagnetic interference/electromagnetic pulse (EMI/EMP) protection and consequently pose flight safety risks.

Another reason for replacing cadmium is the plating process uses hazardous chemicals and generates hazardous waste. The Environmental Protection Agency (EPA) has targeted 17 hazardous substances for reduction or elimination because of their volume of use, toxicity, persistence, and mobility. Some of these "EPA-17" toxic chemicals include cadmium, nickel, and chromium. The Air Force is currently eliminating the use of EPA-17 chemicals to reduce worker exposure to hazardous materials, reduce maintenance costs, and meet increasingly stringent pollution control requirements.

An estimated 5 and 10 million connector pairs are in the Air Force, Air Force Reserves and Air National Guard combined fleet. Approximately 0.8 milligrams of cadmium are in each connector pair. If the liberal assumption is made that all connectors are cadmium-coated, there may be up to several metric tons of cadmium plated just on connectors.

The goal of the project this report describes is to identify potential alternative coatings for connectors that do the following:

Project Goals

- ❑ Meet the minimum performance requirements to protect systems from EMI and EMP/lightning strikes; and
- ❑ Have less potential for a negative impact on the environment and preferably do not contain any EPA-17 materials.

1.2 Project Tasks

Project Tasks

To meet the objective and goals of this project, the Air Force Research Laboratory (AFRL) identified the following tasks:

Task A. Identify current coating processes used with electronic connectors including post-process requirements and conversion coatings.

Develop requirement performance and acceptance criteria for potential replacement technologies.

Task B. Review and document commercial and laboratory technologies that may replace the current hazardous applications.

Task C. Prepare a test protocol and conduct testing on alternatives. The test protocol will include specific connector modifications and coating parameters with requirements for economic cost, adhesion, electrical conductivity, and long-term corrosion.

Task D. Conduct technical meetings and provide consultant support at technical interchanges.

1.3 Research Methodology

To address Task A and Task B, connector stakeholders were surveyed over the telephone. Stakeholders included Original Equipment Manufacturers (OEM) contacts, other Military Service contacts, connector manufacturers, plating shops, and research institutions. Contact reports are in a separate document. Section 8 lists various workshops, conference proceedings, technical journals, and textbooks from which data was gathered.

1.4 Objectives of This Report

Report Objectives

The objectives of this report are the following:

- ❑ Summarize the results of the initial research; and
- ❑ Identify alternative plating materials to conventional cadmium plating that may meet minimum performance requirements.

1.5 Organization of the Report

Report Organization

This report is organized into the following sections:

- ❑ Section 1, Introduction
- ❑ Section 2, Connectors in Modern Aircraft
- ❑ Section 3, Issues with Connectors
- ❑ Section 4, Current Methods to Address Connector Issues
- ❑ Section 5, Connector Research
- ❑ Section 6, Potential Alternative Coatings and Configurations
- ❑ Section 7, Summary
- ❑ Section 8, References
- ❑ Appendix A, Current Connector Requirements
- ❑ Appendix B, Approaches to Address Electrical Connector Bond Degradation

2 Connectors in Modern Aircraft

Electrical connectors come in a wide range of shapes, sizes, configurations and materials. Connectors are used in all electronic systems, which include modern aircraft (planes and helicopters), ground systems (automobiles and tanks), and floating systems (ships and submarines). The connectors provide electrical connections between electrical cables and electronics boxes and allow easy replacement of cables and components.

According to several connector stakeholders, a modern aircraft has between 500 and 2,000 electrical connectors. Assuming an average of 1,000 connectors per aircraft, the 6,300+ fixed wing aircraft in the inventory of the Air Force, Air Force Reserves, and Air National Guard (AW&ST 1998) have between 5 and 10 million mated connector pairs. At an estimated average cost of $25.00 (DLA 1998), the value of these connectors is on the order of $125M to $250M.

2.1 Types of Connectors

Connectors are typically constructed of aluminum, titanium, stainless steel, or composites. Coatings such as cadmium, nickel, and other materials contribute toward electrical, environmental, and mechanical performance.

Electrical connectors require a coating that conducts electricity and repels elements of the weather. Cadmium plating is used because it is an excellent corrosion inhibitor and has relatively high electrical conductivity. Nickel is an excellent conductor but is not quite as corrosion resistant; it is often used as an underplate. A chromate conversion coating is applied (Alodine solutions) to achieve the highest amount of corrosion protection and provide the color (olive-drab) requirement. Olive-drab cadmium plated connectors generally contain a nickel underplate, cadmium plate, and a chromate conversion coating.

The ruggedness of cylindrical connectors makes them useful in hostile environments. A cylindrical connector consists of two mating halves, or shells, each containing multiple pins or sockets. There are several military specifications that form the basis of procurement for cylindrical connectors; several are listed in Table 1.

Table 1. Partial List of Military Connectors

MILSPEC	Title
MIL-C-38999	Connectors, Electrical, Circular, Miniature, High-Density, Quick Disconnect (Bayonet, Threaded, and Breech Coupling), Environmental Resistant, Removable Crimp and Hermetic Solder Contacts, General Specification For
MIL-C-5015	Connectors, Electrical, Circular, Threaded, AN Type, General Specifications For
MIL-C-83723	Connectors, Electrical, Circular, (Environmental Resisting), Receptacles and Plugs, General Specifications For
MIL-C-28840	Connector Electrical, Circular Threaded, High Density, High Shock Shipboard, Class D, General Specifications For

The Air Force Research Laboratory and representatives from the System Program Offices at Aeronautical Systems Center (ASC) indicated that the MIL-C-38999 connector is a common connector used on aircraft (USAF 1998a). This document limits all discussions and research to the MIL-C-38999 connector. For more information on MIL-C-38999 requirements, see Appendix A, *Current Connector Requirements*.

MIL-C-38999 specifies a wide array of base metals, plating materials, sizes, pin configurations, etc. This study focuses on the Class W (Environmentally resisting – corrosion resistant plating), which consists of an olive-drab (chromate conversion coating) cadmium plate over a suitable conductive underplate (nickel).

2.2 Grounding for EMI Protection

Electrical connectors provide electrical connections between electrical cables and electronics boxes and allow easy replacement of cables and components. The cables are jacketed to protect the wires in the cable from electromagnetic interference (EMI) and electromagnetic pulse (EMP). In order for this protection to function adequately, the shielding must be well grounded. Grounding is accomplished by (a) electrically connecting the shields from multiple conductors to the backshell of the connector and (b) electrically connecting the backshell to the components and/or the aircraft frame.

To help ensure that the shielding is uniform, it is important that the connection to components and/or aircraft frame be electrically connected around the whole perimeter of the connector shell (360°). Because the EMI ground is carried along the shielded cable through the connector shell, there needs to be electrical continuity between the shield and the connector shell.

Electrical bonding is achieved when electrical components are electrically connected by means of a low impedance conductor. The interconnection should be made so that the mechanical and electrical properties of the current path are determined by the connected members and not by the fasteners. The connection of the grounding shield must maintain its mechanical and electrical properties over an extended period of time.

Kodali (1996) provides a summary of general guidelines for good bonds that can be applied to connector shell-to-plate (airframe or box) bonds:

Guideline for Good Bonds

- Bond surfaces should be smooth and clean.
- Non-conductive finishes should not be used.
- Fastening method should provide enough pressure to hold the surface contact.
- Bonding should be made with similar metals to avoid corrosion and intermodulation generation (see box below).
- Protective finishes may be used to protect the bond from moisture and other causes of corrosion.

Intermodulation

Intermodulation is also known as the "rusty bolt" effect. In metal-to-metal joints in bonding and grounding, non-linear junctions formed by corrosive surfaces generate intermodulation interference products. Intermodulation may reduce the EMI shielding effectiveness of a connector backshell mounted to a dissimilar metal. More on the "rusty bolt" effect can be found in Kodali (1996).

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3 Issues with Connectors

The following key issues involving electrical connectors used on Air Force aircraft form the main drivers for this AFRL project:

Key Issues

- ☐ Unacceptable (off-spec) electrical bonds.
- ☐ Flight safety issues.
- ☐ Environmental, health and safety concerns.

3.1 Unacceptable (Off-Spec) Electrical Bonds

Unacceptable bonds may be defined as bonds that do not meet the military specification, regardless of whether the bond provides adequate grounding for EMI protection. In this section, the following topics are addressed:

- ☐ Increased resistance over time.
- ☐ Field disconnect between OEM specifications and field maintenance.
- ☐ Proper specification for good bonds.

3.1.1 Increase in Resistance Over Time

Military specification MIL-C-38999 requires a maximum shell-to-shell bond resistance of 2.5 mΩ for the cadmium-plated (Class W) connector. MIL-STD-464 (1998) extends the 2.5 mΩ requirement for an installed connector, where the connector back shell is connected to the mating surface (usually aluminum treated with a chromate conversion coating).

The problem occurs after the connector back shell is fastened to the airframe (or box). Initial measurements may meet the 2.5 mΩ requirement, but over time the bond degrades and the resistance slowly increases.

Many individuals contacted noted that the industry has known about the problem of bond degradation for many years. It seems that every military and commercial aircraft manufacturer has had to face this bonding issue at one time or another.

In the summer of 1996 the Air Force, in conjunction with Lockheed Martin Fort Worth, performed a field measurement study to determine the bond resistance on electrical connectors on F-16s at several Air Force and Reserve bases (USAF 1996). The results of the field measurements showed a wide variation in bonding values. The bond deterioration was caused by an oxidation layer that is formed when a cadmium-plated connector is mated to an aluminum plate that has a chromate conversion coating.

The cause of bond deterioration was also examined in a couple of key projects:

- ☐ Lockheed-Martin Tactical Systems (Woodrow 1996). LMTS studied the electrical bond between a cadmium-plated connector and an aluminum substrate to determine the cause of the bonding degradation. They connected two plates with different combinations of substrates, coatings, and films and subjected them to DC current in ambient conditions. LMTS found degradation of the electrical bond when only cadmium and aluminum were present. They felt that it was due to corrosion in which the aluminum is oxidized in an environment with oxygen and water forming aluminum oxide, a non-conductor.

- University of Dayton Research Institute (Ziegenhagen 1997a). UDRI examined the basis of corrosion between a cadmium-plated electrical connector with a nickel underplate and chromate conversion coat and an aluminum plate representing the aircraft skin. Oxygen was added and the torque was varied for different setups. Analysis revealed that oxides had formed on the surface of the connector, causing the resistance to rise. Added oxygen caused oxide buildup at a faster rate, while greater torque slowed down the resistance creep.

Thus, there is agreement among connector stakeholders that oxidation build-up is the primary cause of bond degradation.

What is the Basis for 2.5 mΩ Bond Resistance?

Several rationales have been put forward for the 2.5 mΩ resistance requirement. The most concise discussion of this issue can be found in the appendix of MIL-STD-464. There are three theories:

- The requirement stems from the early days of metal aircraft design when the aircraft skin was used for the return circuit;
- The requirement stems from a need to protect the aircraft from a lightning strike; and
- It was attainable and indicative of good metal-to-metal contact and higher resistance was likely to be an indicator of improper quality control.

Modern aircraft primarily use balanced circuits, so the first reason is largely obsolete. In the discussion about lightning strikes, MIL-STD-464 points out that a DC resistance of 2.5 mΩ would translate to an induced voltage on the cabling of 500 volts from a 200KA strike. MIL-STD-464 also indicates a more realistic resistance value of 10 mΩ between shield to electrical components, though it still advocates 2.5 mΩ for individual faying surfaces.

Reference: MIL-STD-464 1997

3.1.2 Field Disconnect Between OEM Specifications and Field Maintenance

An investigation into whether aircraft operators in the field routinely monitor bond resistance uncovered anecdotal evidence pointing to a disconnect between the manufacturers specification and field maintenance procedures. When Mr. Howard Swanson, an F-16 Wiring Engineer at Ogden ALC, was asked about connector failures on the F-16 during routine maintenance (Swanson 1998), he replied that connectors do not fail often, and most are never replaced. Most of the F-16's connector problems are due to physical damage, such as one that had been badly bent or banged or one with damaged threads. Connectors in the wheel well are changed much more frequently because they are exposed to more harsh environments. Mr. Swanson noted that F-16 maintenance technicians only check the shell-to-plate resistance when looking for grounding problems (i.e., there is no scheduled checks on bond resistance). They do not keep records on connector failures.

Mr. George Slenski, AFRL Project Manager, noted that field bond resistance measurements are taken to include the fasteners (Slenski 1998). A lower bond resistance can be achieved when the fasteners are included, thus there are fewer connector "failures." However, EMI engineers oppose using the fasteners to determine bond resistance, citing the need for a uniform 360° conductive path around the faying surface to provide adequate EMI protection.

Cadmium-coated circular connectors (MIL-C-38999) are quite robust in the field and are well-designed to withstand the harsh environment on a military aircraft. More evidence needs to be collected on bond failures in the field to conclude that bonding is causing system failures due to grounding problems (see Section 3.2).

3.1.3 Proper Specification for Good Bonds

Some EMI engineers feel that the DC bond resistance is not an adequate measure of the "goodness" of the bond. The purpose of the low resistance bond is to provide adequate grounding for EMI protection. Several EMI engineers contacted as part of this study indicated that 2.5 mΩ was the maximum acceptable bond resistance, and some considered it too high.

EMI is generally in the form of radio frequency (RF) interference caused by other on-board electronics or external sources. Some argue that a better measure of a good bond is the transfer impedance, and Lockheed Martin Skunkworks has already instituted these procedures (Blackburn 1998). The counter argument is that if a bond passes the DC resistance test, it will most likely pass the transfer impedance test. Because transfer impedance tests are more complex and costly, DC resistance tests are preferred if the end result is the same.

Transfer Impedance

Transfer impedance is the relationship between the current flowing on the outside of a shield to the voltage developed on the inside. Transfer impedance is used to measure EMI shielding effectiveness, as described in MIL-C-1377.

The two ends of a test connector are attached to a short length of the shielded cable. One of the cables is terminated in a short circuit for shielding integrity, and the other is connected to the signal source though a cable adapter. The ammeter, which measures the center conductor RF current, is mounted inside a shielded box with a shielded viewing window.

The RF voltage is measured with a voltmeter probe fitted with balanced probe leads. The shielding effectiveness is calculated in terms of the transfer impedance Z_t by measuring the center conductor current, I_0, and the maximum voltage between the two connector shells, V_m separated by a distance, l, and is expressed by:

$$Z_t = \frac{V_m}{I_0 \cdot l}$$

References: Woodrow 1996; Kodali 1996; MIL-STD-1377 1971

3.2 *Flight Safety Issues*

System failure is a primary flight safety concern. System failures may be caused by EMI or EMP/lightning strikes. This section addresses the impacts of both on flight safety.

Data was sought on which aircraft system failures were caused by bad electrical bonds and inadequate grounding, but only anecdotal evidence was collected.

A whistleblower suit prompted an investigation regarding the safety of General Electric (GE) engines (General Electric 1995). In June 1994, an employee alleged that GE engines were unsafe due to electrical bonding failures. Following an 11-month review of the GE F110-GE-129 engine, which powers the F-16, the Air Force concluded that there were no concerns for flight safety related to the electrical bonding. As part of this review, the Air Force conducted field tests to evaluate the performance of these engines in various electromagnetic interference environments under variable bonding conditions. The FAA had concluded earlier in 1994 that there were no safety issues involving electrical bonding on GE's commercial engines. GE responded by stating that no GE engine had ever failed due to electrical bonding problems, out of over 40,000 GE military and commercial engines worldwide and over 200 million flight hours over several decades.

One individual surveyed for this project noted that if a failure on a system occurs in the field due to a badly bonded connector, it would not be recorded as a failure of the connector or wiring system (Walker 1998). A bad connector bond that causes a failure of the flight control system would be regarded as a failure of the flight control system. Further investigation may lead to identification of the bad connector, but this information would not be recorded nor returned to the engineers at the manufacturing facility.

System redundancies may also lower the risk for catastrophic system failures due to inadequate connector shielding or grounding. A bad connector may cause a system to fail, but double and triple redundant systems will allow the safe return of the pilot and aircraft.

3.2.1 EMI Protection

The F-16 System Program Office has studied the potential impact of EMI protection due to degraded connector bonds. While specific data is not available on their findings, Mr. George Slenski, AFRL Project Manager, indicated that the F-16 engineers found that most connectors were providing adequate protection, even up to bond resistance levels of 10 mΩ (Slenski 1998). The F-16 engineers calculated the probability of a critical system failure (an uncommanded maneuver) in terms of number of failures per number of sortie hours that could be attributed to EMI leakage at connector joints. Study findings were not available during the preparation of this report, and it is not known whether serious impacts on flight safety were identified.

According to Bobby Crumb, Lockheed Martin Aeronautical Systems, SAE AE-8C Connector Subcommittee Chair, EMI protection is paramount (Crumb 1998). Mr. Crumb has determined that an initial bond resistance of 0.1 mΩ maximum is required on new aircraft to provide adequate protection from EMI. Mr. Crumb indicated that the 0.1 mΩ requirement was based on calculations and analysis but could not be validated in tests because of the number of variables involved. The lower bond resistance requirement can be attributed to modern aircraft electronics that run at much lower voltages, making the signal-to-noise ratio a much more critical parameter.

3.2.2 EMP/Lightning Strike

EMP/lightning strike is another area of concern in flight safety. Although direct lightning strikes on connectors or cable shields are rare, serious hazards can result when lightning strikes a composite airframe (Welch c.1987). Composite airframes are less able than metal structures to protect internal components against high current surges. Tests performed by the Navy showed that when connector components fail due to lightning strike, the high current can vaporize the plating off composite connectors, leaving the EMI shielding vulnerable (Bond and Smith 1993). Military and commercial aircraft generally avoid flying in or near electrical storms due to the inherent danger and risk of lightning strikes.

3.3 Environmental, Health and Safety Concerns

Plating, conversion coating, and grinding processes each cause environmental, health and safety impacts from listed EPA-17 toxic materials. In this section, we briefly examine these issues relative to connector manufacturing and processing.

EPA-17 Industrial Toxins
Benzene
Cadmium and Cadmium Compounds
Carbon Tetrachloride
Chloroform
Chromium and Chromium Compounds
Cyanide Compounds
Dichloromethane (Methylene Chloride)
Lead and Lead Compounds
Mercury and Mercury Compounds
Methyl Ethyl Ketone
Methyl Isobutyl Ketone
Nickel and Nickel Compounds
Tetrachloroethylene
Toluene
1,1,1-Trichloroethane
Trichloroethylene
Xylenes

Electrical connectors purchased by OEMs or Logistics Centers are already pre-plated with conductive and protective finishes. Some OEMs provide additional processing. Most will conversion coat the contact area (with Alodine) prior to fastening. Others will grind off the cadmium and nickel plate to provide an aluminum-to-aluminum bond. These processes expose workers at the manufacturer, plating facility and OEM to hazardous materials.

The Air Force has established several goals to reduce toxic chemical releases from installations and in weapon system manufacturing to protect human health and the environment. In addition, there are stringent EPA and OSHA regulations governing releases of chemicals used in connector manufacturing and.

The Air Force Pollution Prevention Strategy (USAF 1995) states that the Air Force is committed to "minimizing or eliminating the use of hazardous materials and the release of pollution into the environment." Regarding Air Force acquisition programs, the Air Force Pollution Prevention Strategy directs weapon system managers to institute policies and procedures to minimize or eliminate the use of toxic chemicals including (in order of preference) ozone depleting substances, EPA-17 industrial toxins, and all other toxic and extremely hazardous materials. Cadmium, nickel, and chromium are examples of EPA-17 industrial toxins (see box on the left) and are often used for plating connectors and other aerospace parts.

Cadmium and chromium are also listed as the EPA and Department of Health and Human Services Agency for Toxic Substance Disease Registry's (ATSDR) Top 20 Hazardous Substances for 1997 (ATSDR 1998). This list, maintained annually by ATSDR as directed by EPA's Superfund regulations, is based on chemicals that pose the largest risk to human health and the environment.

The Navy and the Army have both initiated cadmium elimination programs. Both have research efforts aimed specifically at cadmium coated electrical connectors (see Section 5).

In Europe, there is a concerted program to eliminate cadmium plating across the continent. The European Union established a law prohibiting the use of cadmium. However, there is an exemption to this law for aerospace parts; therefore, electrical connectors used on aircraft may continue to use cadmium plating (Williams 1998a).

3.3.1 Cadmium

Cadmium is a common plating material that has excellent corrosion resistance, lubricity, and electrical conductivity.

Cadmium is plated onto the aluminum connector using electrolytic plating. The process involves one or more pretreatment steps (e.g., degreasing, acid etching), a plating step, and post-treatment steps (e.g., rinsing, conversion coating).

In the plating step, the part is placed in a tank or plating barrel/rack, and then connected to the electrical circuit. The predominant active chemical in the plating bath is cadmium cyanide. An electrical bias draws cadmium ions to the part, where they are reduced to cadmium metal.

According to EPA's *Locating and Estimating Emissions* document on air pollution sources for cadmium emissions sources, no air pollution control measures are currently being used on cadmium electroplating tanks (EPA 1993). In fact, EPA considers the emission potential from cadmium electroplating tanks to be <u>extremely low</u>. The EPA's emission for cadmium for <u>uncontrolled</u> cadmium plating is 0.040 grains/A-hr (2.59 mg/A-hr) (EPA 1996). Assuming a current density of 250 A/m^2 with a tank area of 5 m^2, this equates to 3.2 g/hr of emissions.

OSHA, on the other hand, has very specific regulations on protecting workers from cadmium exposure (OSHA 1998a). OSHA requires employers to determine if any employee may be exposed to cadmium at or above the action level (2.5 $\mu g/m^3$, 8-hour time-weighted average). If the employer exceeds the permissible exposure limit (5 $\mu g/m^3$, 8-hour time weighted average), the employer must prepare reports, conduct medical screening, and conduct costly monitoring activities.

The health effects of cadmium include acute and chronic impacts and are summarized in the following box. EPA also notes that serious impacts can result from cadmium particles that are too large to be drawn deep into the lungs but small enough to enter the tracheobronchial region of the lung. This can lead to bronchoconstriction, chronic pulmonary disease, and cancer of that portion of the lung (OSHA 1998b). Particles that remain in the nose and mucous membranes because of their size can be absorbed into the blood (OSHA 1998b). This is a concern when grinding off the cadmium plate as several OEMs are doing (e.g., Boeing, Bell Helicopter, Lockheed Martin).

OSHA issued a health hazard bulletin on cadmium overexposure in the aircraft repair industry (OSHA 1989). Workers in a landing gear shop who had been grinding cadmium-plated parts were exposed to 85 times the ceiling limit for airborne cadmium.

Health Effects of Cadmium

- The acute (short-term) effects of cadmium in humans through inhalation exposure consist mainly of effects on the lung, such as pulmonary irritation.
- The kidney is the major target organ in humans following chronic inhalation and oral exposure. Cadmium is a cumulative toxicant in some organs such as the kidney; the cessation of exposure does not lead to a decrease in effect.
- Cadmium has been shown to be a developmental toxicant in animals, resulting in fetal malformations and other effects, but no conclusive evidence exists in humans. These effects could be seen from both acute and chronic exposures.
- Human and animal studies have seen an increase in lung cancer from long-term inhalation exposure to cadmium. EPA has classified cadmium as a Group B1, probable human carcinogen of medium carcinogenic hazard.

Source: EPA 1998

3.3.2 Nickel

Nickel is used as an underplate on cadmium-plated connectors. Underplates prevent alloying elements in the base material from gradually diffusing to the surface and degrading the interface. The nickel underplate is 5-6 times thinner than the cadmium plate.

Nickel is also plated on several classes of MIL-C-38999 connectors, providing bond resistance levels of 0.1 mΩ and higher temperature/thermal cycling performance. Although they are less corrosion resistant, nickel-plated aluminum and composite connectors are likely to find increased usage because they provide better EMI protection for sensitive electronics.

Nickel can be plated using electrolytic or autocatalytic (electroless) methods. The baths used to electroplate nickel can be formulated to deposit nickel with a range of properties. For instance, nickel deposits can range from being mirror bright for decorative applications, to dull but mechanically robust for wear and corrosion prevention applications. AP-42 emission factor for electrodeposited nickel is 0.63 grains/A-hr (40.8 mg/A-hr) (EPA 1996). Assuming current density of 250 A/m^2 with a tank area of 5 m^2, this equates to about 50 g/hr of nickel emissions.

In the case of electroless nickel, neither electrodes nor an external source of current are required to plate. Instead nickel salts are reduced to metal by chemical means. Electroless nickel baths are usually nickel-phosphorus (from hypophosphite ion, $(H_2PO_2)^-$) (Dennis and Such 1993).

Electroless nickel does not form an air emission since it does not form hydrogen or oxygen gas to produce a mist.

The most common adverse health effect of nickel in humans is an allergic reaction such as a skin rash at the site of contact. Less frequently, people who are sensitive to nickel have an asthma attack following exposure to nickel (ATSDR 1988b).

Lung effects, including chronic bronchitis and reduced lung function, have been observed in workers who inhaled large amounts of nickel. Current levels of nickel in workplace air are much lower than in the past, and today few workers show symptoms of nickel exposure (ATSDR 1988b).

The Department of Health and Human Services (DHHS) has determined that nickel and certain nickel compounds may reasonably be anticipated to be carcinogens (EPA 1998). Cancers of the lung and nasal sinus have resulted when workers breathed dust containing high levels of nickel compounds while working in nickel refineries or nickel processing plants.

3.3.3 Chromate Conversion Coating

Conversion coating is the chemical treatment of a metal surface to produce an adherent coating composed of chromates, oxides, phosphates, or other protective chemicals. Chromate conversion coatings are produced by combining chromium compounds with other water-soluble inorganic materials. During the treatment process, the surface of the metal is converted to a layer of chromium salts to produce the desired decorative or functional properties (USAF 1997).

The active ingredient in these solutions is hexavalent chromium (chromium (VI)) in chromate (CrO_4^{-2}) and dichromate ($Cr_2O_7^{-2}$) chemical forms.

Conversion coatings are widely applied to a variety of metal surfaces to provide corrosion protection and to allow paint adhesion. In the case of an aircraft skin, the conversion coating is sprayed on, allowed to dwell for a specified timeframe (seconds to minutes), then rinsed off with water. For electrical connectors, the conversion coating is applied by immersion in a treatment tank then rinsed off with water. In either case, the rinse water containing chromium is collected and treated to remove chromium prior to discharge into a sanitary sewer.

The chromium (VI) in the chromate conversion coat can cause health effects if ingested (though poor industrial hygiene) or inhaled when in spray form. OSHA has set personal exposure limits (PEL) for chromic acid (the main worker exposure hazard involved in chrome plating) at 0.1 milligrams-per-cubic meter (mg/m^3) Dermal exposure to chromium (VI) may cause contact dermatitis, sensitivity, and ulceration of the skin (EPA 1998).

The respiratory tract is the major target organ for acute (short-term) and chronic (long-term) inhalation exposures. Symptoms of acute exposure include dypsnea, coughing, and wheezing, while perforations and ulcerations of the septum, bronchitis, decreased pulmonary function, pneumonia, and other respiratory effects have been noted from chronic exposure (EPA 1998). Human studies have clearly established that inhaled chromium is a human carcinogen, resulting in an increased risk of lung cancer. EPA has classified chromium (VI) as a Group A, human carcinogen of high carcinogenic hazard (EPA 1998).

For the OEMs that grind off the cadmium plate down to the aluminum substrate prior to fastening to the aircraft, the dust may allow chromium (VI) to be inhaled and therefore pose health hazards. Considering that the conversion coating is 10 to 20 times thinner than the cadmium plate, and the PEL is lower for chromium than cadmium, the health risks attributed to chromium are presumed to be small but not insignificant.

A variety of conversion coatings have been formulated without the use of chromium (VI). MIL-C-5541E (1990) calls out a Class 3 conversion coating for electrical bonding applications. Alodine 2000 is the only non-chromate conversion coating that has met the Class 3 specification (JG-APP 1996).

4 Current Methods to Address Connector Issues

This section summarizes the results of the telephone survey conducted between June and September 1998. It describes the approach each of the OEMs used to address the issues identified in Section 3.

Most of the individuals contacted were EMI or wiring engineers. Table 2 provides a summary of OEM approaches.

<u>Summary:</u>

- ❑ Two manufactures do not have bonding issues and are not considering replacements (Northrup Grumman, Teledyne Ryan Aeronautical).
- ❑ Two manufactures (Northrup Grumman, Raytheon Aircraft) modified procedures to achieve good bond resistance. (Northrup instituted strict process controls; Raytheon bonds within one hour of conversion coating.)
- ❑ Nickel-plated connectors are used by a variety of OEMs as replacements for cadmium plated connectors (GE Aircraft Engines, Lockheed Martin, Raytheon, Hamilton Standard).
- ❑ Some OEMs (BF Goodrich, GE Aircraft Engines, Raytheon [ground systems]) use stainless steel connectors as cadmium-plated connector replacements.
- ❑ Raytheon (ground systems) considered ion vapor deposited (IVD) aluminum plated connectors, but did not make the change due to "political issues."
- ❑ At least three manufacturers (Boeing, Bell, Lockheed Martin) are grinding off the cadmium plating down to the aluminum surface, treating the surface with a conversion coat, fastening, then sealing.
- ❑ Hamilton Standard is considering the use of gaskets.
- ❑ Raytheon TI System uses conductive grease in conjunction with cadmium coated connectors.

OEMs do not appear to view environmental, health, and safety issues regarding the use of cadmium, nickel, or chromium on the connector backshells to be a driver for the development of new backshell materials.

Table 2. OEM Approach to Meeting Bond Resistance Requirement

Organization	System	POC	Approach
Bell Helicopter	V-22	Rex Wade	• Grind off cadmium and nickel plate, conversion coat, seal.
BF Goodrich	Interface harness supplier	Les Travis	• Use a low-mass stainless steel backshells
Boeing Commercial	Multiple	Greg Van Overstraaten	• Grind cadmium off, mount, seal outside with sealant
Boeing Defense and Space	Not identified	Tom Woodrow	• Use a conductive sealant (PR-2000 Courtalds)
GE Aircraft Engines	Engine supplier	Steve Hanak	• Use a stainless steel and nickel plated connectors • Use different military specification (MIL-B-5087) which does not have 2.5 milliohm requirement mandatory
Hamilton Standard	Flight and engine control supplier	Luke Orsini	• Evaluating gasket material (IRAD) • Use nickel plate where possible
Lockheed Martin	Joint Strike Fighter	Joe Walker	• Specify Class M finish (electroless Ni plate)
Lockheed Martin Control Systems	Multiple	Dave Pepin	• Clean base aluminum with chemical solvent
Lockheed Martin Skunkworks	B-2	Keith Blackburn	• Use composite connector plated with nickel • Specify transfer impedance
Lockheed Martin Tactical Systems	F-16	Doug Howard	• Have not found a suitable alternative; no change to current process or materials • Examined conductive adhesive, but contained nickel so did not substitute
Lockheed Martin Aeronautical Systems	F-22	Bobby Crumb	• Grind off cadmium • Use nickel-plated composite connectors
Northrup Grumman	B-2	B. Watlington Bob Zark	• Strict process controls (improved workmanship and materials)
Raytheon	Multiple ground systems	Doug Coggeshall	• Use nickel-plated stainless steel connectors • Came close to using IVD aluminum
Raytheon Aircraft	Not identified	Howard Jordan	• Make bond within 1 hour of conversion coat
Raytheon TI Systems	Multiple surface systems	Michael Turk	• Add a silver-loaded silicon grease
Teledyne Ryan Aeronautical	Global Hawk	Sam Halderman	• Use composite connectors with Class W (cadmium) plating • No problems meeting bond resistance requirement

5 Connector Research

5.1 Research Efforts

Several studies have attempted to identify the cause of connectors failing to meet the 2.5 mΩ bond resistance requirement, including the AFRL-sponsored research performed by the University of Dayton Research Institute:

- *Connector Bonding Resistance Tests and Materials Analysis* (Ziegenhagen 1997a).
- *NyBron®-Plated Electrical Connector Bonding Resistance Test (Materials Analysis)* (Ziegenhagen 1997b).
- *Connector Bonding Resistance Tests Using Ion Vapor Deposited Aluminum Plating (Materials Analysis)* (Ziegenhagen 1998).

Air Force Engineering & Service Laboratory (Tyndall AFB) sponsored research on the use of IVD aluminum to replace cadmium plating, performed by Boeing St. Louis (formerly McDonnell Douglas):

- *The Substitution of IVD Aluminum for Cadmium* (Holmes, Muehlberber, and Reilly 1989).

US Army (TACOM) sponsored a study on alternatives to cadmium plating, performed by Ocean City Research Corporation:

- *Alternative Material Selection System for Cadmium (AMSS-Cd), Version 1* (TACOM 1997).

Their study on alternatives to cadmium-plated electrical connectors is on-going.

Joint Group on Acquisition Pollution Prevention (JG-APP) is currently sponsoring a cadmium plating elimination demonstration and validation program. The work is carried out by Boeing Information, Space, and Defense Systems in Kent, Washington. The focus is on examining two alternatives: tin-zinc and nickel-zinc (JG-APP 19978).

A limited amount of information and test data were obtained on the following projects:

- Aluminum Connectors Coated with IVD Aluminum and Chromate Conversion Coating (Lockheed Martin) (Smith 1997).
- Connector Electrical Bonding (Lockheed Martin Control Systems, (Pepin 1996).
- Electrical Bonding Degradation (Lockheed Martin Tactical Systems) (Woodrow 1996).
- Testing of Electrical Bond Promoters (Lockheed Martin Tactical Aircraft Systems) (Kelley 1996).
- Alternatives to Cadmium for Electrical Connectors (JTech 1998).

The following projects were identified, but no information was obtained:

- ASC/LUN sponsored research by Lockheed-Martin. Final report, "Electrical Bonding of Cadmium Plated Connectors Mounted to Aluminum Surfaces" (report not available) (Howard 1998).
- Hamilton Standard is looking at the use of gaskets in an IR&D project (Orsini 1998).
- Navy C-2 program looking at corrosion, comparison of cadmium-plated and nickel-plated composites with and without the use of gaskets. They are also looking at use of Glyptol® paint (Roberts 1998).

The following are current research activities reported by connector manufacturers:

- Raychem has been investigating the use of metal mesh washers between the connector and the aluminum surface (Dutton 1998).
- Amphenol has investigated many different coatings but the information was competition sensitive so they could not provide any details (Davis 1998).
- Cinch Connector Division has started to investigate IVD aluminum (Cline 1998).
- Hi-Rel Connectors indicated that they have found a promising alternative to cadmium, but they are in the process of taking out a patent and would not share any of their discoveries (Payne 1998).
- Deutsch has investigated many different coatings including zinc/iron, zinc/cobalt, and nickel/Teflon®, but the results are preliminary at this time (Harrington 1998).
- Entraco Electrical Interconnect Systems and Components claims to have developed a superior nickel/Teflon® coating system (TTH™) (Entraco 1998).

5.2 Technology Transfer and Dissemination

Dissemination of research findings occurs in various forums. The Air Force Research Laboratory, in conjunction with the Aeronautical Systems Center (ASC) program offices, hosted connector bonding workshops in 1996 and 1997. The goal of the workshops was to evaluate the scope and causes for deterioration of electrical bonds on cadmium-plated connectors. Individuals presented papers demonstrating that cadmium and aluminum chemically react in the presence of water and oxygen to form insulating oxides. Workshop participants proposed a variety of potential solutions, but none were accepted as complete solutions.

The Society of Automotive Engineers (SAE) has been active in the preparation of specifications and other guidance for the aerospace industry. SAE established a standing committee in the Aerospace Electronics and Electrical Systems Division addressing Aerospace Electrical/Electronic Distribution Systems, also known as committee AE-8. This committee has two standing subcommittees that deal directly with connector bonding issues. The System Installation (AE-8A) subcommittee is concerned with electrical wiring systems, although they do not specifically target connectors. The Connector (AE-8C1) committee is responsible for connector specifications. All the SAE committees meet twice a year.

While SAE is responsible for the maintenance of the system and component aerospace commercial specifications, the Electronic Industry Alliance (EIA) is responsible for electronic component specifications for various applications, including aircraft. They have a standing committee entitled "National Connector Standards (Military and Aerospace Devices)" CE-2.0. This committee has a standing subcommittee (CE-2.0.1) which specifically addresses connector plating materials. EIA committees meet three times a year.

The Defense Supply Center Columbus (DSCC) is the main procurement agency for military electronic components. It is responsible for making sure that the equipment meets military requirements. DSCC is also responsible for the maintenance of electronic component specifications and for incorporating new technologies into those specifications. The DSCC holds annual connector standardization meetings.

There are several forums established to discuss issues regarding cadmium elimination:

- The Naval Surface Warfare Center, Port Hueneme Detachment Louisville sponsors an annual corrosion Technology Information Exchanges.
- SAE sponsors a cadmium elimination conferences.
- The National Defense Center for Environmental Excellence (NDCEE), run by Concurrent Technologies Corporation (CTC), sponsors an annual cadmium and chromium elimination workshop.

While these meetings are primarily focused on the elimination of cadmium in general, solutions identified in these forums may lead to possible solutions for eliminating cadmium in electrical connectors.

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6 Potential Alternative Coatings and Configurations

This section presents a list of alternative coatings for aircraft electronic connector applications. A general overview of key properties (conductivity and corrosion) is presented first followed by a discussion of coating technologies.

6.1 Material Properties

The key to the solution to the electrical connector problem is to find a way to make the faying surfaces both electrically conductive and corrosion resistant. For example, many components on aircraft are made from aluminum. Aluminum is an excellent electrical conductor, but it is also very reactive and easily corrodes. Under ambient conditions a native oxide forms on the surface of aluminum that protects against further corrosion. Unfortunately, the native oxide is electrically insulating.

6.1.1 Resistance

The net resistance of a connector is a combination of bulk and interfacial resistance. The bulk resistance depends on the materials from which the connector and coatings are fabricated. Table 3 presents the bulk electrical resistance of selected elemental coating materials. Elements with the lowest resistance (and hence highest conductivity) are silver, copper, and gold. Elements can be alloyed to alter their material properties, including resistance.

Table 3. Bulk Electrical Resistance of Selected Elements

Metal	Resistance (μΩ-cm)
Silver	1.59
Copper	1.68
Gold	2.24
Aluminum	2.65
Zinc	5.9
Cobalt	6.24
Cadmium	6.8
Nickel	6.84
Palladium	10.54
Tin	11
Chromium	12.9
Titanium	42

Source: CRC Handbook of Chemistry and Physics 1986

The interfacial resistance depends on whether an insulating layer forms at interfaces due to corrosion. Interfacial resistance increases when corrosion creates an insulating layer at an electrical interface.

6.1.2 Corrosion

Corrosion is the gradual destruction of a metal or alloy by oxidation-reduction reactions. For example, iron corrodes in the presence of oxygen and an electrolyte (e.g., salt). The net reaction is that iron is oxidized and gaseous oxygen is reduced. The role of the electrolyte is to conduct a charge between microregions where the oxidation and reduction reactions occur. The oxide that forms sometimes protects against further corrosion. Since the oxide that forms on iron is a loose scale, the oxide does not protect against further corrosion.

There are a couple different types of corrosion, including galvanic and electrolytic. When two dissimilar metals are joined, corrosion is possible even in the absence of gaseous oxygen. This is called galvanic corrosion. It is possible to predict which metal will be oxidized and which reduced based on the galvanic series (see Table 4). In galvanic corrosion, materials lower in the series tend to spontaneously oxidize materials higher in the series when placed in physical contact in the presence of an electrolyte. In electrolytic corrosion, an imposed voltage reverses the reaction and causes a material lower the series to be oxidized by one higher.

Table 4. Galvanic Series

Magnesium
Magnesium alloys
Zinc
Aluminum 2S
Cadmium
Aluminum 17ST
Steel or Iron
Cast Iron
Chromium-iron (active)
Ni-Resist
18-8 Chromium-nickel-iron (active)
18-8-3 Chromium-nickel-molybdenum-iron (active)
Lead-tin solders
Lead
Tin
Nickel (active)
Inconel (active)
Brasses
Copper-nickel alloys
Monel (passive)
Inconel (passive)
Chromium-iron (passive)
18-8 Chromium-nickel-iron (passive)
18-8-3 Chromium-nickel-molybdenum-iron (passive)
Silver
Graphite
Gold
Platinum

Source: Dini 1993

6.2 Processes to Coat Connectors

Various processes are available to form a coating on a connector backshell. These include:

- Electroplating.
- Autocatalytic Deposition (Electroless).
- Vapor Deposition.
- Thermal Spray.

Each of these processes is described below.

6.2.1 Electroplating

Electroplating is the process of applying a metallic coating onto a part by passing an electric current through an electrolyte containing a salt of the metal. In electroplating the part to be plated is made the cathode, where reduction reactions occur, and a second electrode (the anode) is present to complete the circuit.

The National Metal Finishing Resource Center identifies a long list of commercially available plating materials, identified in Table 5.

Table 5. Commercially-Available Plating Materials

Brass Bronze Cadmium, CN Cadmium, Non-CN Chrome, Black Chromium, Hard Chromium, Decorative (Cr+3) Chromium, Decorative (Cr+6) Copper, CN Copper, Electroless Copper, Fluoborate Copper, Pyrophosphate Copper, Strike (CN) Copper, Strike (non-CN) Copper, Sulfate	Gold, CN Gold, Non-CN Indium Iron Lead Lead-Tin Nickel, Black Nickel, Bright Nickel, Electroless, Boron Nickel, Electroless, Phosphate Nickel, Electroless, Other Nickel, Fluoborate Nickel, Semi-Bright Nickel, Sulfamate Nickel, Sulfate Nickel, Teflon	Nickel, Tin Nickel, Watts Nickel, Woods Palladium Platinum Rhodium Silver CN Silver Non-CN Tin, Acid Tin, Alkaline Tin-Lead Zinc, Acid Zinc, CN Zinc, Non-CN Zinc-Cobalt Zinc-Iron Zinc-Nickel-Cadmium Plating - Olive Drab

Source: NMFRC 1998

<u>Advantages:</u>

- Uses conventional processes; used pervasively.
- Is relatively inexpensive, depending on raw material cost.
- Does not require extensive training to operate baths.

Limitations:

- Requires a large volume of chemical for plating baths.
- Generates air emissions (from release of hydrogen gas).
- Baths require cyanide (although non-cyanide formulations are available).
- Generates wastewater that requires treatment prior to discharge (although solvent-based baths are also available for some plating materials).

6.2.2 Autocatalytic Deposition (Electroless)

In autocatalytic deposition, metal salts are reduced to metal by chemical means and deposited on the substrate. An electrical current is not required, hence the popular term "electroless plating."

Advantages:

- Is possible to plate parts that are electrically non-conducting, since no electrodes are required.
- Has superior plating uniformity compared to conventional electroplating.
- For nickel, produces much harder plating surfaces than from conventional electrolytic baths (Dennis and Such 1993).

Limitations:

- Is between 5 and 10 times more expensive than conventional plating (Dennis and Such 1993).

6.2.3 Vapor Deposition Technology

Vapor deposition refers to processes in which a coating is formed from gas phase precursors. There are two categories of vapor deposition processes: physical (PVD) and chemical (CVD). In PVD, the solid coating material is made into the vapor phase by physical means such as evaporation or sputtering. The vapor plume is allowed to condense on a part to form a coating. CVD is the process of chemically reacting a volatile compound of a material to be deposited with other gases to produce a nonvolatile solid that deposits on the part (Ohring 1992). Hybrid processes exist that make use of two or more techniques. For instance, plasma-assisted CVD makes use of a plasma to promote chemical reaction and decomposition at lower substrate temperatures.

Ion vapor deposition (IVD) of aluminum is a type of PVD process. Pure aluminum is evaporated from boats to create a vapor. The part to be coated is biased at a high negative voltage in a partial pressure of argon gas, which causes a glow discharge to form. A fraction of the aluminum atoms that pass through the discharge become positively charged, and are accelerated toward the part.

Almost any inorganic material can be vapor deposited. A limited range of organic compounds can be vapor deposited.

Advantages:

- PVD is dry and non-hazardous.
- CVD and certain PVD processes are not limited to line-of-sight.
- A wide variety of metals and ceramics can be deposited on various substrates.

Limitations:

- PVD cannot coat holes and inner surfaces of tubes.
- PVD and CVD are performed using vacuum hardware, which requires a significant capital investment.
- CVD is generally performed at relatively high substrate temperatures in order to promote chemical reactions (300-600°C depending on the coating).

6.2.4 Thermal Spray

Thermal spray is a coating process conducted under open-air conditions. The coating material is fed by wire or from powder into a flame where it is melted. A high velocity stream of compressed air or other gas propels particles of molten material onto a prepared substrate. Depending on the substrate, bonding occurs either due to mechanical interlocking with a roughened surface, by localized diffusion and alloying, or by Van der Waals attraction. There are three basic categories of thermal spray technologies: plasma spraying, detonation gun, and flame spraying (Bunshah 1982).

Most inorganic materials (metals, ceramics) can be deposited using thermal spray.

Advantages:

- Is a dry process that does not require vacuum hardware.
- Performed under ambient conditions.
- Deposits are typically hard and well adhered to the substrate.

Limitations:

- Is a line-of-sight process; it is not possible to coat the inside of tubes or deep recesses.
- Is coarse, so coated parts must be machine finished. This is an extra production step that increases cost.

6.3 Potential Alternative Coatings and Configurations

This section identifies potential alternative coatings and provides a rationale why each coating may be applicable to connectors.

6.3.1 Ion Vapor Deposited Aluminum

Ion vapor deposited aluminum, or IVD aluminum as it is commonly known, was developed by McDonnell Douglas in St. Louis (currently

Boeing). The coating was originally developed to solve corrosion and hydrogen embrittlement problems.

IVD aluminum is dense, pure metallic aluminum. It shows excellent adhesion to most substrate materials and forms a good surface for painting. The IVD process is versatile and adaptable to a wide variety of part, shapes, and sizes. It is not confined to line of sight, but it cannot coat inside tubes or deep recesses.

IVD is successfully used as an alternative to cadmium-plated parts, such as fasteners, on some military aircraft. Earlier studies suggest that poor lubricity may cause galling in fasteners (Ingle 1991). A representative from an IVD aluminum job-shop indicated that this is only true if the threads are extremely tight (Little 1998). Parts are glass peened in order to compact the coating and create a more uniform surface.

Low, stable bond resistance appears to be a favorable feature with IVD aluminum. In tests conducted by the former McDonnell Aircraft Co., IVD aluminum provided a 500 to 1000 hours salt-spray requirement per MIL-C-38999 (Holmes et al 1989). In a bonding resistance test conducted by Ziegenhagen (1998), IVD aluminum connectors subject to 500 hours salt fog had a final shell-to-plate bond resistance of 19 mΩ while the cadmium-plated connector rose over 30 mΩ (in 340 hours salt fog and remaining time to 500 hours in ambient conditions).

The IVD coating process is covered by military, industrial, and company specifications. Military specification MIL-C-83488, Revision C Amendment I specifies three classes and two types. Table shows the minimum number of hours of salt spray tests that each class and type must undergo. The class callout determines the coating thickness. The type callout specifies post treatment with a conversion coating:

- Type I is as coated.
- Type II is with a chromate seal per MIL-C-5541.

Type II coatings give the maximum corrosion protection and are used almost exclusively.

Table 6. Salt-Spray Test

Class (thickness, inches)	Type I (minimum)	Type II (minimum)
Class 1 (0.01 minimum)	504 hours	672 hours
Class 2 (0.0005 minimum)	336 hours	540 hours
Class 3 (0.0003 minimum)	168 hours	336 hours

IVD aluminum is included as a new class (Class V) of connector in the proposed revisions to MIL-DTL-38999K (1998). The proposed IVD coated connectors have the same shell-to-shell conductivity requirement as cadmium-plated (Class W) connectors.

Patented IVD chambers, called Ivadizers®, are currently being sold by Abar Ipsen. There are currently about 70 Ivadizers® throughout the world. The Navy has seven at the Naval Air Stations, the Air Force has seven at various bases, and major aerospace manufacturers have their own. There are also a number of smaller job shops with Ivadizers® in the United States.

Ivadizers® have been successfully operated for over 20 years. Their operation requires a relatively large amount of training. IVD coatings experts at AAA Plating in Compton, CA undergo a minimum 6-month on-the-job training program to become skilled at Ivadizer® operation. The operators must learn how long to leave the part in the chamber to achieve the coating thickness required on various complex shapes. In addition, Ivadizers® require skilled operators to maintain the equipment in good working condition (Little 1998).

Members of the SAE AE-8C committee meeting expressed concern over IVD aluminum coated electrical connectors. They contend that while there is sufficient test data on corrosion, there is not enough data to determine whether IVD aluminum will meet all other MIL-C-38999 requirements (e.g., vibration, shock, fluids).

6.3.2 Aluminum Electroplating

The aluminum electroplating process was developed by Siemens AG in Germany. This process includes standard metal cleaning with caustics and acids, a nickel strike, water removal, plating in an aluminum electroplating cell, and an optional surface chemical post treatments. The electrolyte contains aluminum alkyls and metal fluoride in toluene (TACOM 1997). All water and oxygen must be kept from the electrolyte in order to prevent unwanted chemical reactions that shorten its life (TACOM 1997). Capital costs for electrodeposited aluminum coating facilities are very high (Brown 1988).

The Air Force Needs Assessment Summary (AFRL 1997) reports that electroplated aluminum provides excellent corrosion protection under acidic conditions and can survive relatively high service temperatures. It shares the same advantages as IVD aluminum with the additional ability to plate inside diameters and complex shapes. AlumiPlate, Inc, Minneapolis, MN, owns the current patents for this process.

Lockheed Martin F-16 has examined the aluminum electroplating as a replacement for cadmium and determined that it has very desirable properties (USAF 1998). They tested IVD aluminum and electroplated aluminum on grounding strips and were very impressed with the performance of the electroplated aluminum, particularly with corrosion resistance. The vendor, AlumiPlate, has a newly developed process that doesn't require a nickel underplate. However, the electrodeposited parts still require a conversion coating.

The downside of the AlumiPlate process is that it is a closed process based on solvents rather than water. While it does not generate a wastewater that requires treatment, the solvent (toluene) creates a potentially hazardous work environment due to its flammability and toxicity. Toluene is also an EPA-17 chemical targeted for elimination. Representatives from AlumiPlate claim that the process is safe and that all emissions are captured and recycled back to the system (Vallejo 1998). AlumiPlate offers to license the technology to interested parties.

6.3.3 Aluminum-Ceramics

Aluminum-ceramic protective coatings have long been used in turbo-machinery applications. By suspending aluminum particles in a glass-like ceramic matrix, aluminum-ceramic coatings are very durable and can withstand temperatures of up to 1500°F. This coating is used in automobile brake rotors, aircraft landing gear axles, jet engines, and industrial fasteners. Aluminum-ceramic coatings are also used as an alternative to zinc coatings in electrical grounding screws since they are more conductive with less galvanic effects (Simmons 1994). Specific data on conductivity were not available in the literature, but assumed to be lower than aluminum.

6.3.4 Aluminum Bronze

The aluminum bronzes are essentially copper-aluminum alloys, containing up to about 13.5% aluminum, small amounts of manganese and nickel, up to 4% iron for the purpose of hardening the alloys, and the remaining amount copper.

Aluminum bronzes are strong, possess excellent corrosion resistance and good anti-frictional characteristics, and resist scaling and oxidation at elevated temperatures. The good anti-frictional characteristics of these alloys make them suitable for bearings, bushings, rollers, and gears. They are also used in marine hardware, shafts, pump, and valve components for handling seawater, sour mine waters, non-oxidizing acids, and industrial process fluids.

No information on the electrical properties of aluminum bronze plating was available. However, since it is composed primarily of aluminum and copper, it is presumed to be an excellent electrical conductor.

Aluminum bronze is reportedly heavier than cadmium plating, although an exact weight comparison was not available.

Aluminum bronze has been successfully used as a cadmium plating replacement in Europe for the past several years. It has been in use for at least 15 years on a connector known in the UK as a pattern 608, a threaded connector with a two start square thread and contains an insert similar to MIL-C-26482 Series 1. In recent years, connector manufacturers in the UK have created an aluminum-bronze connector that is exactly the same as MIL-C-38999. This connector is in use by other European navies and is specified by a European specification CECC75201-002 (Williams 1998b).

Amphenol Aerospace in the USA and Amphenol Ltd. in the UK have both proposed that the material be included as a new class in MIL-DTL-38999K, which is likely to be discussed at a coordination meeting in January 1999 (Williams 1998b).

6.3.5 Zinc Alloys

Zinc is typically used to enhance corrosion resistance in salt-rich environments. Zinc sacrificially protects steel from corrosion. Since zinc is very reactive, the only way to achieve long corrosion protection is to electrodeposit thick coatings, or apply a better chromate conversion coating. Unfortunately, in most cases, zinc deposits thicker than 0.0005 mil are brittle and crack if bent or formed. Some of the limitations of pure zinc can be overcome by using alloys of zinc, such as cobalt, iron, nickel, and tin.

In spite of their improved properties compared to plain zinc, these alloys are still considered poor cadmium substitutes when lubricity, solderability, and low contact resistance are considered (AFRL 1997). Reports also indicate that zinc alloys are prone to whisker growth (Brooman 1993).

Typical alloys include:

- Zinc-cobalt.
- Zinc-iron.
- Zinc-nickel.
- Tin-zinc.

Each alloy is discussed below.

6.3.5.1 Zinc Cobalt

When a small percentage of cobalt (0.25-0.90%) is co-plated with zinc, the resulting alloy gives better corrosion protection than zinc alone. The corrosion protection can be further enhanced by using a chromate conversion coating. A passivated zinc-cobalt coating provides 200 hours of resistance to white rust, and 500 hours to red rust (Brown 1988). The cost to plate zinc-cobalt is only slightly higher than pure zinc. Both acidic and alkaline plating baths are available. The downside of the baths is that the percentage of cobalt in the plate is process sensitive.

The baths are reported to have high plating efficiencies and plating speeds (TACOM 1997).

Amphenol Aerospace reports that they have a proprietary black zinc cobalt solution that they can use to plate aluminum connectors which meets the current specification. They are currently using black zinc cobalt on parts they ship to Europe (Stenman 1998).

ASTM B840 "Standard Specification for Electrodeposited Coatings for Zinc Cobalt Alloy Deposits" provides the performance requirements for these coatings.

6.3.5.2 Zinc Iron

Only a single type of bath is available for zinc-iron electroplating. It is an alkaline non-cyanide bath. The percentage of iron in zinc-iron is typically 0.25 to 0.90%. Conflicting reports makes it unclear whether zinc-iron alloys exhibit better corrosion protection than pure zinc coatings (Budman 1997; TACOM 1997). Its corrosion protection is reduced after exposure to 240°F for just one hour (Budman 1997). However, zinc-iron alloys can be chromate conversion coated, which may increase corrosion protection. Deutch reported promising results from their internal R&D testing of zinc-iron coatings (Harrington 1998).

6.3.5.3 Zinc-Nickel

Zinc-nickel coatings have good ductility at 5-15% nickel, and good resistance to whisker growth at 15% nickel (Brooman 1993). These coatings usually have good adhesion properties and can have a maximum service temperature of 400°F (Brooman 1993). The alloy is hard (250-310 Vickers) and more scratch resistant than other zinc alloys (Budman 1997).

The coating accepts a chromate conversion coating. The corrosion resistance in the ASTM B-117 Salt Fog test is typically over 1,000 hours to red corrosion (Budman 1997). It is three times more corrosion resistant than cadmium (USAF 1994). The corrosion resistance reportedly increases with nickel content, up to approximately 15-18 percent (TACOM 1997). However, recent tests reported by JTech (1998) show that zinc-nickel coatings over aluminum backshells degraded significantly after 500 hours of salt-spray, from 6.7 mΩ to a final 92 mΩ shell-to-shell resistance.

Zinc-nickel also shows good adhesion. The coatings are used on fasteners on electrical transmission structures and television coaxial cable connectors (Brooman 1993). Zinc-nickel baths are also available without the use of cyanide (USAF 1994). A downside of zinc-nickel is that it shows lower lubricity and higher electrical resistance than cadmium (AFRL 1997).

Boeing has developed a proprietary zinc-nickel plating process that provides the same level of corrosion protection as cadmium plating (Bates 1994). The Boeing process contains a deposit of 10-18% nickel, with the balance zinc. The plate is usually passivated with a chromate conversion coating to achieve the maximum corrosion protection. Tests conducted by Bates (1994) evaluated the Boeing process on zinc-nickel plated steel, and found that it provided superior hydrogen embrittlement performance and corrosion resistance comparable to cadmium plating.

ASTM B841 "Standard Specification for Electrodeposited Coatings for Zinc Nickel Alloy Deposits" provides the performance requirements for these coatings.

6.3.5.4 Tin-Zinc

Tin-zinc plating baths contain 10-30% zinc (Brooman 1993, TACOM 1997). This coating has the highest lubricity of any plated zinc alloy and is similar to cadmium with regard to stress corrosion cracking (AFRL 1997). This coating also has salt spray resistance comparable to cadmium and is resistant to SO_2 and high humidity environments. This coating has relatively low resistivity that increases with zinc content and a low stable contact resistance when sealed with a chromate conversion coating (Simon 1985). The drawbacks are that it has lower lubricity and higher electrical resistance than cadmium. Another drawback is that the tin may leach out at high (>175°C) temperatures since tin has a lower melting temperature. Tin-zinc alloys are often used to coat electrical chassis (Brooman 1993).

6.3.6 Nickel

Nickel plating is currently offered in several MIL-C-38999K classes. Nickel may be applied using either electrolytic or electroless plating techniques. The coatings are relatively hard with good wear and abrasion resistance. The coatings are free of "whisker" growth and electromigration found in cadmium and zinc coatings. Nickel provides good corrosion protection in alkaline environments but performs poorly in sulfur-containing environments (Brooman 1993, TACOM 1997). Nickel performs worse than cadmium in marine environments (TACOM 1997). Nickel does not give sacrificial protection to a base metal; instead it forms a protective barrier against corrosion. Also, it does not form a thick oxide layer (TACOM 1997). Nickel coatings are reportedly more expensive than cadmium (Brooman 1993).

6.3.7 Nickel-Boron

Nickel-boron coatings have good electrical conductivity and are hard. They are often used on electrical contacts. Ziegenhagen (1997b) found that nickel-boron coatings provided excellent bond resistance levels between two faying surfaces. In a separate assessment, Ziegenhagen (1998) also found Nybron® (proprietary nickel-boron plating material made by Techmetals, Inc.) performed extremely poorly in a salt environment (Ziegenhagen 1998).

Better substrate corrosion protection may be provided by impregnating (after deposition) using materials like PTFE (Polytetrafluoroethylene, i.e., "Teflon®) (USAF 1994). However, PTFE has non-conductive properties and therefore would impact electrical performance.

6.3.8 Nickel-Teflon®

Nickel-Teflon® coatings have traditionally been used on applications that require a lubricious surface, such as carburetor components, pneumatic cylinders, valve parts, and release coatings for molds (Dennis and Such 1993). These coatings, however, have reportedly not stood up to the salt spray corrosion test.

Independent tests of the nickel-Teflon® coating on an aluminum backshell reveal that the shell-to-shell resistance does not meet bond resistance requirements after the salt spray test (JTech 1998). The data presented shows a shell conductivity of 4 mΩ prior to salt spray, which degraded to 743 mΩ after only 240 hours of salt spray.

Entraco (1998) markets a new nickel-Teflon® plating process for electrical connectors that is purported to have superior salt spray (fog) performance (1,500+ hours) compared with cadmium (500+ hours) while maintaining comparable conductivity as cadmium.

6.3.9 Nickel Cobalt

Nickel cobalt alloy coatings have been found to provide a hard and wear resistant surface (Brooman 1993). There is also a nickel cobalt alloy coating impregnated with a solid lubricant (PFTE or Teflon®) that is promoted to add lubricity. This coating, however, has a high surface resistivity which makes it a poor alternative for connector applications (Brooman 1993).

In data presented by JTech (1998), nickel-cobalt coatings did not meet the initial 2.5 mΩ shell-to-shell requirement, and degraded significantly after only 320 hours of salt spray.

6.3.10 Tin-Nickel

Tin-nickel coatings typically contain 33-35% nickel and are hard and brittle. This coating has good wear and abrasive resistance and does not tarnish easily. Tin-nickel coatings are used on fuse caps, coaxial cable connectors, and electrical switch gear (Brooman 1993). No other information on this coating was available in the literature.

6.3.11 Palladium-Nickel

The noble metals have high reduction potentials that render them inert to all but the most aggressive corrosive chemistries. For instance, MIL-G-45204 specifies a gold plating of 100 microinches or more for high reliability electrical applications. One might dismiss noble metals as too expensive for an electrical connector application; however, the cost can be reduced by using a lower cost metal than gold, such as palladium, and by alloying the palladium with nickel. In fact, a palladium-nickel alloy (80% palladium) shows superior mechanical properties compared to gold while remaining nearly as noble.

Palladium-nickel has been used for many years as a hard, durable, and corrosion resistance electrical contact finish for the telecommunications, computer, aerospace and automotive industries.

Lucent Technologies has developed an improved electroplating bath for palladium-nickel marketed under the trade name Pallatech™. The significant advance in Pallatech™ over previous bath chemistries is the ability to deposit a low porosity finish at coating thicknesses below 1 micron. Low porosity is important in order to prevent deterioration of contact resistance due to corrosion of the base metal through a pore. Lucent Technologies claims that the Pallatech™ plating bath is non-hazardous and that all constituents can be recycled.

A typical protective coating structure consists of a nickel underplate (4 microns), a palladium-nickel layer (0.25 to 2.5 microns) and a flash of hard gold (gold-cobalt alloy). Nickel is frequently plated prior to precious metal plating to form a diffusion barrier against contamination of the precious metal by base metal constituents. Nickel also provides a hard supporting layer. The purpose for the final hard gold flash is to achieve a highly unreactive surface.

The contact resistance of palladium/nickel (as-deposited) is 2.5-8 mΩ (Dennis and Such 1993). A thin flash of gold will lower the resistance to 1.5 to 2 mΩ.

The primary cost for plating palladium-nickel is the cost of the bath chemicals. The cost of the chemicals depends on the price of palladium. At present, palladium salt used in the bath costs $350 per troy ounce.

This translates to roughly 10 cents per square inch per micron of palladium-nickel.

In related work, Lucent Technologies has published the results of salt spray tests in which a palladium-nickel plating was used under a zirconium nitride coating only 0.5 microns thick (Kudrak 1996). The salt spray test used is called Copper Accelerated Acetic Acid Salt Spray Test (CASS) (ASTM B 368-85). The automotive industry uses this test to estimate the life expectancy of chrome plated bumpers. A 60-hour CASS test is considered to represent ambient exposure up to 10 years. Without the palladium-nickel underplate, after 60 hours the base metal was badly corroded, whereas with the palladium-nickel underplate no corrosion was visible. This suggests a thin palladium-nickel plating may prove to be sufficient to meet corrosion requirements.

6.3.12 Nickel-Indium Alloy

Dennis and Such (1993) suggest that nickel-indium alloys may be considered alternative coatings for electronics applications. They report that previous studies show that they have promising corrosion resistance and low contact resistance that remained stable over time. No other information on this coating was available in the literature.

6.4 Substrate Material

6.4.1 Composites

Composites used for electrical connectors are typically made of fiberglass and resin and are plated with a conductive layer. They are resistant to most chemicals and environments (TACOM 1997). Composite connectors are 20-25% lighter than similar-sized aluminum versions (CTI 1998, JTech 1998).

MIL-C-38999J (1990) Class J and M connectors are composite-based. Class J is an olive drab cadmium plate with suitable underplate and Class M is an electroless nickel plating. Both must withstand 2,000 hours of salt spray test in qualification and 500 hours for periodic inspections. Composite connectors are therefore extremely corrosion resistant.

6.4.2 Stainless Steel

Stainless steels, or other corrosion resistant steel (CRES), are ferrous-based materials that have heavy alloy additions of other metals, typically chromium or nickel (TACOM 1997). Stainless steel connectors have a higher weight and cost than an aluminum connector, but do not usually require other coatings for added corrosion protection. MIL-C-38999J (1990) specifies a 50 millivolt potential drop (shell-to-shell) equivalent to a 50 mΩ bond resistance for stainless steel connectors. Thus, stainless steel connectors may not meet the 2.5 mΩ bond resistance requirement for EMI protection of aircraft systems.

Recent tests with 316 stainless steel backshells revealed a shell conductivity of 2 mΩ. After 1,000 hours of salt spray, the shell conductivity degraded to 4 mΩ (JTech 1998). This suggests stainless steel backshells may have the capability to maintain a low bond resistance over time, even in a harsh environment.

It is also important to note that stainless steel contains nickel, chromium, and other hazardous materials (e.g., 304 has 18-20% chromium and 8-11% nickel; 316 has 16-18% chromium and 10-14% nickel). By using stainless steel as a replacement for cadmium-plated aluminum connectors, the overall use of chromium and nickel will increase significantly.

The weight factor between a stainless steel connector with a similar-sized olive-drab cadmium connector with an aluminum base material is approximately 2:1 (JTech 1998). If weight is an issue (as with military aircraft), stainless steel backshells may not be a realistic alternative.

6.4.3 Titanium

Titanium offers some benefits over aluminum-based connectors. Titanium is very resistant to corrosion and is very strong. However, the electrical conductivity is low compared with cadmium (WMIN 1998). Titanium is an expensive raw material because it is a rare metal.

The proposed revision MIL-DTL-38999K proposes a new class of titanium connectors, Series III and IV Class R. It has been proposed that these connectors have the same requirements as the cadmium-plated connectors except higher salt-spray requirements (1,000 hours).

The weight factor between a titanium connector with a similar sized olive-drab cadmium connector with an aluminum base material is approximately 2:1 (JTech 1998). If weight is an issue (as with military aircraft), titanium backshells may not be a realistic alternative.

Titanium may have compatibility problems with fluids (e.g., deicing fluids).

In a recent test with titanium connectors, the shell conductivity did not degrade after 1,000 hours of salt spray. However, the initial shell-to-shell conductivity was measured at 10 mΩ and therefore does not meet 2.5 mΩ requirement for EMI protection (JTech 1998).

6.4.4 Magnesium

Electrical connectors fabricated from aluminum are die cast. If the connector is a complex shape, it must be machined after casting, which increases cost. Magnesium alloys can be injection molded to directly form complex parts without costly machining, although some machining may be required because of the geometries.

For an aircraft connector application, the principal advantage of magnesium compared to aluminum is reduced weight. A connector made from magnesium weighs 30% less than one made from aluminum. Magnesium also has favorable electrical properties. The bulk resistivity of magnesium is 4.45 $\mu\Omega$-cm, which is less than nickel, chromium or cadmium, but slightly greater than aluminum (2.65 $\mu\Omega$-cm).

The major limitation of magnesium is that it is highly reactive. No other commonly used structural metal is more reactive than magnesium. Once ignited, magnesium readily burns. The use of magnesium in aircraft must therefore be carefully considered in light of its risk to flight safety. It is commonly used on automobiles.

When placed in electrical contact with aluminum, magnesium will be preferentially oxidized. However, alloys of magnesium show greatly improved corrosion behavior compared to elemental magnesium and protective coatings can be applied. For example, ThixoTech Corporation, a specialist in injection molding of magnesium parts, reports that magnesium AZ91D corrodes eight times slower that carbon steel and four times slower that aluminum 380 (ASTM B-117 salt fog test) (ThixoTech 1998).

6.4.5 Hybrid Connectors

In this report, hybrid connectors are defined as a connector that consists of a metal sleeve over-molded with composite material (plastic resin) (as opposed to connectors that have both electrical and optic contacts). The interior metal sleeve provides a continuous metal electrical path from the backshell interface to the mounting flange.

Experimental hybrid connectors were developed to reduce weight and improve corrosion resistance (Bond and Smith 1993). Hybrids have about 15 percent weight savings over conventional aluminum connectors (Welch c.1987). The ITT Cannon's KJAH hybrid connector prototype was designed to be a direct replacement for MIL-C-38999 Series III metal connectors:

> *"The hybrid connector preserves the mechanical strength, shielding effectiveness and lightning strike resistance traditionally expected from metal connectors, and may be used in any application for which a metal connector is suitable."*
>
> *Welch (ITT Cannon) c.1987*

The Navy tested a hybrid connector (ITT Cannon's KJAH hybrid connector) in lightning strike tests. Hybrid connectors showed only slight evidence of damage during the six succeedingly increasing peak currents from 0.5 kA through 20 kA (Bond and Smith 1993). Cadmium-plated aluminum connectors performed only marginally better.

ITT Cannon never commercially produced the hybrid connector, citing the fact there was no interest in military markets. It is likely due to the fact hybrid connectors are expensive to manufacture and therefore require large volumes to make costs competitive with other connector classes (O'Hirok 1998).

If airframes are made to provide EMI/EMP and lightning protection, most Program Managers (PMs) will select the lighter weight composite connectors as the connector of choice. Otherwise, PMs might consider using hybrid connectors over metal and composite connectors if the airframes, such as composite airframes, are not providing EMI/EMP and lightning protection.

6.5 Best Potential Alternatives

Table 7 summarizes the information found on 15 different coatings, 3 different alternative substrate materials, and the hybrid connector. There may be more materials and alloys that have applicability to connector shells that have not been identified.

Of the 15 alternative coatings presented, seven are nickel alloys. Since nickel is an EPA-17 chemical and targeted for elimination, these alternatives rate low on an environmental desirability scale.

The zinc alloys are also problematic. They appear to have (in general) poor conductivity and corrosion resistance. Deutch has a promising (proprietary) zinc-iron plating that may be applicable to electronic connectors. No other zinc alloys are recommended for detailed assessments.

If nickel were not an issue, palladium-nickel and nickel-indium alloys may be a good selection to test. They are currently only used on contacts. Their applicability to connector shells is not known and worthy of investigation.

Similarly, a proprietary nickel-Teflon® product may have solved some of the issues regarding bond degradation after corrosion tests. This product may be worthy of further investigation.

IVD aluminum has already been tested on connector backshells. They show a great deal of promise and are currently under review in the new MIL-DTL-38999 Revision K. IVD aluminum opponents feel that issues with lubricity may limit its use on connector backshells. Additional environmental tests, other than corrosion, are also required.

Electrodeposited aluminum may be a good cadmium replacement. It conventionally requires a nickel underplate, although owners of the technology have developed advances in the technology such that it may not require the nickel underplate. The AlumiPlate process is a closed process based on toluene, and there are concerns over the safety of the process. Since electrodeposited aluminum is a fairly new technology, it is recommended for further investigation.

Since weight is an issue with aircraft systems, titanium and stainless steel are not preferred alternatives. Stainless appears to have an edge on titanium due to its low bond resistance. However, stainless steel contains chromium and nickel in the alloy.

Hybrid connectors offer exciting possibilities. Several years ago, the manufacturers thought that hybrids might be able to replace conventional metal connectors, with added weight savings and corrosion protection. However, there has been no interest in the military market and they are not in production. Hybrids may be a good choice for composite aircraft.

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Table 7. Summary of Alternatives

MATERIAL	ADVANTAGES	LIMITATIONS
	ALTERNATIVE COATING	
IVD Aluminum	• Functions at a service temperature up to 925°F. • Does not induce hydrogen embrittlement or solid metal embrittlement (important for steel-based substrates). • Can coat complex shapes. • Is a dry process and does not generate hazardous waste or require rinse waters. • Has good adhesion to the substrate.	• Is porous and only reach maximum corrosion protection after being sealed with a conversion coating containing chromium. • Cannot coat inside tubes or deep recesses. Note: Electrical connectors do not contain deep recesses. • Is a relatively soft coating that is not suited for applications that require a high degree of erosion or abrasion resistance. • Requires skilled operators due to equipment complexity.
Electrodeposited Aluminum	• Provides excellent corrosion protection under acid conditions. • Can withstand high temperatures. • Able to plate complex shapes; not limited to line-of-sight.	• Requires high capital costs. • Requires nickel, an EPA-17 chemical, underplate.
Aluminum Ceramics	• Are very durable. • Able to withstand high temperatures (up to 1500°F). • May have adequate conductivity; specific data was not available.	• May have high resistivity.
Aluminum Bronze	• Are strong. • Possess excellent corrosion resistance properties. • Have good anti-frictional characteristics. • Likely to possess good electrical properties.	• Potentially more heavy than cadmium plating.
Zinc Cobalt	• Enhanced corrosion protection over zinc, especially with a chromate conversion coating.	• Information on conductivity was not available, but presumed to be poor (USAF 1994).
Zinc Iron	• None identified.	• Has limited corrosion protection, especially at high temperatures.
Zinc Nickel	• Possess good ductility and adhesion. • Resists whisker growth. • Is a hard alloy with good scratch resistance.	• May have problems with electrical bonding after salt spray. • Has higher electrical resistance than cadmium.
Tin Zinc	• Is corrosion resistant to a similar level as cadmium. • Has stable resistivity over time when chromate conversion coated.	• Has lower lubricity. • Has higher electrical resistance than cadmium. • May not stand up to 175°C for sustained periods.
Nickel	• Has good corrosion resistance in alkaline environments. • Provides a protective barrier to base metal. • Remains stable over time.	• Performs worse than cadmium in marine environments. • Is more costly than cadmium. • Contains nickel, an EPA-17 chemical, targeted for elimination.

MATERIAL	ADVANTAGES	LIMITATIONS
Nickel-Boron	• Has low electrical bond resistance.	• Performed poorly in salt environment. • Is very brittle, not ductile. • Contains nickel, an EPA-17 chemical, targeted for elimination.
Nickel-Teflon®	• Is excellent for applications where low friction and wear resistance is required.	• May have problems with electrical bond after salt spray; new formulations (e.g., Entraco) may have solved this issue. • Contains nickel, an EPA-17 chemical, targeted for elimination.
Nickel Cobalt	• Provides a wear-resistant, hard coating.	• Has high contact resistance. • Potentially prone to corrosion. • May have problems with electrical bond after salt spray. • Contains nickel, an EPA-17 chemical, targeted for elimination.
Tin-Nickel	• Provides good wear and abrasion resistance.	• May be brittle. • Contains nickel, an EPA-17 chemical, targeted for elimination. • May not stand up to 175°C for sustained periods.
Palladium Nickel	• Is chemically inert. • Demonstrates sustained high electrical conductivity in electrical contact applications.	• Is a thinner plate (a few microns vs. 12 microns for cadmium plating); the abrasion and salt spray resistance is not known. • Contains nickel, and EPA-17 chemical targeted for elimination.
Nickel Indium Alloy	• Shows promising corrosion resistance. • Has low contact resistance.	• Contains nickel, an EPA-17 material, targeted for elimination.
ALTERNATIVE SUBSTRATES		
Composites	• Provide a 20-25% weight savings. • Can withstand 2,000 hours of salt spray.	• Is plated with nickel or cadmium, both EPA-17 chemicals.
Stainless Steel	• Shows promising electrical bond resistance over time in corrosive (salt-spray) tests. • Has low contact resistance. • Does not require additional coatings for corrosion protection (i.e., fewer processing steps).	• Is heavier and more costly than aluminum. • Contains chromium and nickel in the alloy, both EPA-17 chemicals.
Titanium	• Exhibits excellent strength and corrosion resistance.	• Is heavier and more costly than aluminum.
Magnesium	• Is injection molded, requiring less processing of the actual connector. • Provides a 30% weight savings. • May be able to resist corrosion four times longer than aluminum (Thixo Tech 1998).	• Is highly reactive and will readily burn if ignited. • Has slightly higher bulk resistivity than aluminum. • Can handle temperatures only up to 150°C
Hybrid Connector	• Shows good performance in lightning strike. • Reduces weight. • Improves corrosion resistance.	• Is costly to produce; requires mass production.

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7 Summary

The objectives of this report were to summarize the results of initial research on the topic of electrical connectors and to identify potential alternative plating materials to cadmium that may meet minimum performance requirements. This section summarizes the research and analysis and provides recommendations on the future of this project.

7.1 Summary of Findings from Initial Research

A detailed investigation was conducted of the underlying issues involved with the use of electrical connectors on military aircraft. The issues can be categorized in three areas:

- Unacceptable (off-spec) electrical bonds.
- Flight or system safety impacts.
- Environmental, health and safety concerns.

The following conclusions were made regarding the unacceptable (off-spec) electrical bonds:

- Gradual increase in resistance is due to oxidation between aluminum and cadmium plate.
- There is a disconnect between the manufacturer's requirements for good bonds and field maintenance.
- The exact measurement of the "goodness" of a bond is system-specific; 2.5 mΩ (or less) is the standard used today and is driven by EMI and EMP/lightning strike concerns.

There appears to be inadequate data on the impact on flight and system safety, specifically:

- The probability of a catastrophic failure is low but the exact risk is not known.
- Risks to flight and system safety are becoming more critical as electronic power requirements shrink (i.e., noise-to-signal ratios are getting larger).

The following conclusions were drawn regarding environmental, health and safety issues:

- Impacts are primarily at the connector manufacturer or plating facility, not the OEM.
- Some OEMs grind off the cadmium coating, along with the chromate conversion coat and the nickel underplate, causing potential health and safety issues.
- Connector materials (cadmium, nickel, and chromium) are toxic and targeted for elimination.

The results of a telephone survey of OEMs to identify the methods in which they were addressing the issues are presented in Table 2. The

OEMs do not appear to view environment, health, and safety issues as a primary driver for the development of new connector backshell materials.

7.2 Summary of Potential Alternatives

The research that has been conducted on alternatives to cadmium-plated connectors and cadmium-plating (in general) points to considerable effort at the following:

- Characterizing the potential causes of bond degradation.
- Identifying and/or testing potential alternatives.

Dissemination of research findings occurs in various forums. The Air Force Research Laboratory in conjunction with the Aeronautical Systems Center (ASC) program offices has hosted ad-hoc connector bonding workshops. The SAE and EIA have several standing committees whose charters address electrical connectors and electronic systems. In addition, several organizations sponsor workshops and conferences aimed at cadmium elimination.

A wide range of candidate replacement materials are presented in this report. There are no alternatives identified in this report that greatly exceed cadmium as replacements on electrical connectors. Over half of the coating replacements contain nickel or require a nickel underplate, which is problematic from an environmental standpoint. If nickel alloys are considered, the alloys traditionally used for contacts (palladium-nickel, indium-nickel) may be worthy of further investigation. A proprietary formulation of nickel-Teflon® should be examined. IVD aluminum and electrodeposited aluminum appear to be good candidate replacements. Hybrid connectors are an interesting alternative, combining the benefits of aluminum-plated connectors with composite connectors.

7.3 Recommendations

This project should be continued in order to test new connector materials. If funding is available, the test program should consist of the following:

- Request for submission of alternatives that meet minimum connector performance requirements by connector manufacturers (in teaming arrangements with plating shops, chemical producers, and others).
- Evaluation of candidate replacement materials by an independent test facility.

After the top-rated replacements are identified, a second phase of tests should include the consideration of bond promoters, such as conductive gels, greases, and gaskets.

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Appendix A

Current Connector Requirements

The basic requirements governing aircraft electrical connectors are contained in MIL-C-38999J (1990). This specification calls out the physical and functional requirements of these connectors.

The specification covers four different series of connectors, each with a different function. The series are further subdivided by classes and finishes. Only the Series I and II finish A and B, and Series III and IV Class J and W require the use of cadmium. Series I and II finishes F and N; and Series III and IV Class F, G, M, N and S require nickel.

The principal requirements governing the coating materials used on the connector shell are the salt spray corrosion resistance, the shell-to-shell conductivity, and electromagnetic interference (EMI) shielding.

1 Corrosion Resistance

The salt spray requirement is that "unmated connectors shall show no exposure of base material due to corrosion which will adversely affect performance." Cadmium-plated aluminum connectors (Class W) are tested initially for 500 hours. After the salt spray exposure, the shell-to-shell resistance is allowed to double.

2 Shell-to-Shell Bond Resistance

The resistance is measured by measuring the voltage drop when 1 ampere of current is applied between shell-to-shell (AS13441 1998). Table 8 provides information about the coating requirements and the maximum voltage drop (or mΩ resistance).

Since the primary focus of this effort is to remove the cadmium, and the most stringent requirement for cadmium coated connectors is a 2.5 millivolt drop or 2.5 mΩ resistance, this will be the standard discussed in this project.

3 EMI Shielding

The EMI shielding capability depends on the Series, finish or Class and frequency. The most stringent requirement for cadmium-coated connectors is for Series I, finish B and Series III and IV Classes J and W which require that the minimum leakage attenuation ranges from 90 dB at 100 MHz to 50 dB at 10,000 MHz.

Table 8. Finishes and Requirements

Series I and II finish or Series III and IV Class	Coating	Voltage drop (millivolts)
A*	Ni 0.0002+ inches, Cd 0.0001+ inches	2.5
B*, W†	Olive drab Cd	2.5
C	Nonconductive	N. A.
D*	Sn plate	N. A.
E*	Conductive stainless steel	50
F, G†	Electroless Ni	1
H†, Y†, K†	Conductive stainless steel	10
J†	Olive drab Cd	3.0
M†	Electroless Ni	3.0
N, S†	Electrodeposited Ni 0.0001-0.0002 inches	1

* Series I and II only
† Series III and IV only

4 Proposed Revision K

The Defense Logistics Agency (DLA) recently released a revision of the MIL-C-38999 specification. The new specification will be MIL-DLT-38999K. There are three significant changes to the proposed revision:

1. There is a new requirement that Series I and II, Finish D (fused tin plate) connectors contain a minimum of 3% lead.
2. There are two new Series III and IV Classes; V (IVD aluminum), and R (titanium). These connectors have the similar requirements as the Class W (cadmium plate) connector.
3. There is a new lightning strike test requirement. The specification calls out a Naval Research Laboratory test procedure.

Appendix B

Approaches to Address Electrical Connector Bond Degradation

This section identifies the possible approaches taken to address the need for a low bond (shell-to-plate) resistance that is resistant to corrosion. The focus of all of the approaches identified in this section is how to achieve a low bond resistance rather than eliminating cadmium plate. Therefore, a wider variety of technical solutions are available that will meet connector and bond performance requirements.

1 Penetrating or Removing Native Oxide Layer

This approach involves removing the native oxide layer by etching, physically penetrating the native oxide layer by knurling or embossing, or using expanded metal gaskets. The native oxide layer can also be removed by using pulsed lasers.

Establishing a direct conduction pathway certainly will reduce the resistance, but it will undoubtedly expose the base metal to a greater chance of corrosion. The native oxide layer and coatings help protect the base metal from corrosion. These approaches, therefore, require rigorous corrosion protection measures.

One problem with metal gaskets is that the sealer used may also cause problems with Foreign Object Debris (FOD). In the past when sealers were used over connectors, RTV sealers were used and the RTV material would chip off. Furthermore, the sealers did not prevent corrosion of the base material (Simpson 1998). New sealers will need to have better adhesion and have better corrosion-inhibiting properties than the sealers used in the past.

2 Improve Conductivity of Protective Coatings

This approach involves using more conductive coatings that provide adequate corrosion protection. Alternatives to cadmium plating are considered in this report.

3 Improve the Quality of the Contact

Connector resistance is a function of coating resistance and contact pressure, since contact surfaces are not perfectly smooth. The largest area and greatest contact pressure is the screw surfaces of the fasteners. However, these are not to be considered when measuring the shell-to-plate bonding resistance. If the fasteners are not considered, the contact area is typically the area under the screw heads, and the contact pressure is proportional to the torque applied on the fasteners.

The following methods may be used to increased the contact area/pressure:

- Higher Torque. The specifications do not set the proper torque. Investigations by Ziegenhagen (1998) found a torque of 96 inch-ounces referenced in a previous test report. At high torque there is a risk of stripping the threads and/or the head. There is also a risk of galling the back surface of the connector. Ziegenhagen found little difference in the initial resistance as a function of torque, but the higher torque did make a difference in how fast the resistance degraded with time. This suggests that for torques above 18 inch-ounces, higher torques helped to seal the surfaces from oxidation rather than directly decreasing resistance.
- Increase Contact Area. Approaches to increase contact area include using a screw with a larger head, using more screws, and possibly adding a washer. Spatial and design considerations limit what can be done. Because of spatial and mating systems considerations, these approaches are best to consider for new designs.
- Include Fastener Conduction Path. This approach creates a false sense of a good bond, since the fastener is a good conductor. EMI experts feel that this will not provide adequate 360° shielding. However, this technique is used in the field, and Boeing commercial considers it an adequate measurement of bond resistance (Woodrow 1998).

4 Improve Oxidation Protection

One approach to lower resistance and protect against corrosion is to electrically connect the bare metal of both surfaces and seal the connection to prevent corrosion. Proper installation of connectors calls for the faying surfaces to be unpainted and thoroughly cleaned. Once the surfaces have been mated, the entire assembly is sealed and painted. The procedure recommended for the F-14 (Simpson 1998) calls for grounding holes to be drilled, wire brushed, treated with a chromate conversion coating, then sealed and painted.

Other options to improve oxidation resistance include:

- Add Conductive Gels or Greases. Conductive gels or greases improve the conductivity at the faying surface. They often contain metal flakes or beads.
- Seal Around Contact Surface. Using an adhesive or paint will prevent oxygen or water vapor to reach into the faying surface. One paint that is currently being tested by Navy programs is Glyptol™ 1201 (Roberts 1998, Simpson 1998).
- Alternative Base Material. Stainless steel, titanium, and composite connectors are less prone to oxidation than aluminum.